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THE MILITARY UTILITY OF VERY LARGE AIRPLANES AND ALTERNATIVE FU--ETC(U)
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THE MILITARY UTILITY OF VERY LARGE AIRPLANES AND ALTERNATIVE FUELS*

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INTRODUCTION

Between October 13 and November 14, 1973, aircraft of the Military Airlift Command (MAC) delivered 22,497 tons of equipment and supplies to Lod Airport, Tel Aviv, Israel. Both the C-141A and C-5A aircraft participated in this airlift. Of the total tonnage delivered, C-5As carried 10,757 tons (in 147 sorties) and C-141As the remainder (in 422 sorties) [1].

Although it met its primary objectives, this operation revealed several potentially dangerous shortcomings in U.S. strategic airlift capability, particularly for long-range missions. To a great extent, overseas bases and overflight rights were both denied the U.S. during the 1973 airlift. The U.S. could not obtain diplomatic clearance for MAC to land at its usual bases in the U.K., Spain, Italy, Greece, and Turkey. Furthermore, all aircraft participating in the airlift were forbidden to overfly any land mass. As a consequence, the only en route base available for refueling was Lajes Field in the Azores, Portugal, and the path through the Mediterranean of necessity took numerous zigzags. Had Lajes not been available during the 1973 war, the likelihood of a successful U.S. airlift operation would have been small.

A situation like 1973's could be greatly aggravated if the aircraft could not refuel at the destination. That could happen if the fuel supply system were interrupted (e.g., maritime interdiction of seaborne tankers) or if the available fuel were required for tactical aircraft operations in the battle area. To put this in perspective: the total amount of fuel required for the return leg (from Lod to Lajes) exceeded the amount of equipment delivered to Israel by almost 2000 tons. Had this fuel not been available, the aircraft would have had to depart from Lajes with a full fuel load, off-load equipment at Lod, and return to Lajes without any refueling. That would have reduced the payload of the MAC planes to about what they could carry in nonstop Dover AFB (in Delaware)-to-Tel Aviv flights.

That the C-5A and C-141A aircraft lack impressive performance for the Middle East airlift mission should not be surprising. The characteristics of both airplanes make them most suitable for strategic airlift in support

of a NATO contingency. Even at that, the former Secretary of Defense has suggested that the U.S. needs additional airlift capacity to lessen the time to deploy reinforcement divisions in a conventional NATO war [2].

Military planners thus foresee a need to improve the U.S. strategic airlift. Some think a very large airplane suitable for the airlift role could also execute a variety of other missions. Strategic applications include airborne missile launchers (either ballistic or cruise missiles), tanker support for strategic bombers, and airborne command posts. Typical tactical applications include battle platforms for launching either manned fighters or remotely piloted vehicles, antisubmarine warfare (ASW) and sea-lane control planes, and airborne warning and control systems (AWACS).

In addition to the military implications of the 1973 Middle East war, related events graphically illustrated some of the energy problems facing the U.S. Late in 1973, the Arab members of OPEC (Organization of Petroleum Exporting Countries) instituted an embargo on crude-oil exports to the U.S. and several nations in Western Europe. By the time the embargo was lifted early in 1974, the U.S. petroleum shortfall was estimated to be about 14%. Most consumers recall the principal impact of the embargo as exceedingly long queues at gasoline pumps. However, impacts throughout the economy were severe. The Federal Energy Administration has estimated that the embargo caused a $10-20-billion drop in GNP and, at its peak, resulted in 500,000 additional people being unemployed [3].

The impact of the 1973 embargo on the Department of Defense (DOD), although perhaps less dramatic, was nonetheless significant. During the embargo, the Defense Supply Agency had difficulty in obtaining needed quantities of jet fuel [4]. Despite a drop in jet-fuel consumption as a consequence of less flying, the situation forced a substantial drawdown of pre-positioned war resources which was not alleviated until provisions of the Defense Production Act were invoked in November 1973.

Before the 1973 embargo, oil imported from the Persian Gulf was priced at approximately $4.65 per barrel. After the embargo was lifted in the spring of 1974, the average price was approximately $11.00 per barrel, and since then has been increased by OPEC to about $14.00 per barrel. The impact on the Air Force budget of these increases has been somewhat smaller since the service's fuels are produced from domestic as

well as imported crude oil sources. The price per gallon of JP-4 to the Air Force has increased from 11 cents in June 1973 to 35 cents in July 1974. The average price is presently about 43 cents per gallon [5].

Events attending the 1973 Middle East war increased awareness of our long-term energy problems. The most visible long-term problem, and the one commanding the greatest attention, is the impending depletion of economically recoverable domestic reserves of crude oil. A critical question is the rate of exhaustion. The Energy Research and Development Administration (ERDA) estimates that production can be maintained at or near the 1970 level until the beginning of the 1990s (including Alaskan oil) [6].

Despite uncertainty in future energy supply and demand, one fact emerges clearly. In 1975 petroleum met nearly 50 percent of total U.S. energy demands, domestic petroleum resources accounting for about a third of the total. As noted, domestic petroleum production will remain nearly constant throughout the century. Thus, to meet future demand, the U.S. must begin to rely much more heavily on energy resources other than domestic petroleum. Much of this excess demand has been met to date by increasing petroleum imports. In the near term petroleum imports can be reduced through energy conservation and by greater exploitation of other energy resources--particularly coal and uranium--both of which the U.S. has in relative abundance [6].

Thus, the events of the 1973 Middle East war significantly affected Air Force operations; and since that war the marked increases in the price of jet fuel and the difficulty of obtaining fuel during the embargo have underscored the seriousness of the energy situation.

Late in 1973, Rand's Air Force Advisory Group (AFAG) requested that it examine the implications to the Air Force of the emerging world energy situation. Rand subsequently formulated a research plan that included an investigation of the possible use of alternative fuels. At about the same time, the Vice Chief of Staff directed the Air Force Chief Scientist, then Michael I. Yarymovych, to "organize and chair a Steering Group to develop the research and development plans and to monitor studies on the long-range implications of the energy shortage upon the Air Force's ability to carry out its mission" [7]. In mid-1974, Dr. Yarymovych

requested that Rand's initial detailed evaluation of alternative fuels be made in the context of mission applications of very large airplanes.

The primary motivation for this approach, as should be clear from the earlier discussion here, was the potential need for an airplane with greater range and endurance than existing equipment. Furthermore, previous studies had indicated that some candidate alternative fuels (e.g., liquid hydrogen [8] or nuclear propulsion [9]) would be most attractive in very large airplanes.

The ensuing analysis of mission applications of very large airplanes was jointly conducted by Rand and the USAF Aeronautical Systems Division (under the Deputy for Development Planning, ASD/XR). This paper summarizes some of the major findings of that study [10].

The specific objectives of this work were:

1. Evaluate very large airplanes (VLAs) in the context of existing and possible future Air Force missions, and
2. Determine the most attractive alternative fuel for airplanes of this type.

Moreover, in accordance with a recommendation made in the final report of the Air Force Energy R&D Steering Group [7], subsequently endorsed by the Secretary of Defense [4], we compared the resulting weapons systems in terms of energy effectiveness as well as cost effectiveness.

THE ALTERNATIVES

The value of a VLA would be greater, in terms of system cost and operational flexibility, if a single basic airplane could perform each of the missions discussed earlier. Thus, our goal was to define desirable performance characteristics that would be generally compatible with all of the missions and consistent with the expected state of the art for aircraft entering the inventory between 1985 and 1995.

Analysis indicated that an airplane designed primarily for strategic airlift could be most easily adapted to other missions. The following airplane performance characteristics evolved:

Design radius (flight load-factor of 2.25 g), n mi 3600

Design payload (flight load-factor of 2.25 g), lb 350,000

Cargo compartment, ft
- Max. width 25
- Max. height 13.5
- Length 220

Cruise Mach number .... 0.75 to 0.80

Initial cruise altitude, ft 30,000

Takeoff critical field-length, ft 8000

On a "radius" mission, the airplane delivers its payload at the destination and flies the return legs without taking on additional fuel. The design radius of 3600 n mi provides ranges on the order of 6500 n mi, at least for airplanes using jet fuel (i.e., JP). With the aid of inflight refueling, range/radius of this magnitude can satisfy a worldwide airlift requirement without reliance on foreign bases or fuel at the destination. The corresponding design payload (plus the other requirements) implies a JP-fueled airplane with a maximum takeoff gross weight of about 1.5-2.0-million lb--the largest value thought to be within the expected state of the art in the time frame of interest [9,11].

Screening Alternative Fuels

Many fuels have recently been proposed--some rather casually--for future use in transportation systems [12-14]. Table 1 lists the candidate synthetic chemical fuels that survived our initial screening. We considered other fuels for this list--acetylene, hydrazine, monomethylamine, and propane; but a cursory examination of their characteristics indicated that none promised to be more suitable than those shown, in terms of either physical characteristics (e.g., heat content per pound) or expected synthesis costs.

Table 1

SYNTHETIC CHEMICAL FUELS SCREENED

Fuel	Gravimetric heat of combustion (BTU/LB)	Volumetric heat of combustion (BTU/GAL)	Boiling Point (°F)	Airplane gross weight[b] (10^6 lb)
Synthetic JP	18,600	121,000	210	1.84
Liquid Hydrogen	51,600	30,400	-423	1.28
Liquid Methane	21,500	74,500	-259	1.86
Methanol	8,600	56,700	149	>3.5
Ethanol	11,500	76,000	173	>2.5
Ammonia	8,000	45,600	-28	>3.5
Gasoline[a]	19,100	112,000	257	-

[a]Included for reference only

[b]For 3600 n mi radius mission with 350,000 lbs payload

We screened the six candidates listed in Table 1 further by developing rough conceptual airplane designs for each fuel. The resulting gross weights of those airplanes (sized to the previously described design point) are shown in the rightmost column. Methanol, ethanol, and ammonia prove clearly inferior in this application, owing primarily to poorer heat content per pound.

These results demonstrate that only conventional jet fuel, liquid methane (LCH$_4$), and liquid hydrogen (LH$_2$) offer viable alternatives to JP as chemical fuels. A basic ground rule for this work was that an alternative fuel come from a primary energy resource other than petroleum or natural gas. Each of these promising fuels can readily be synthesized from coal--the most abundant nonrenewable U.S. energy resource (at least until the breeder-reactor program enters commercial service). Indeed, domestic coal reserves exceed the sum of all other U.S. fossil-fuel resources [6].

Liquid hydrcgen, of course, is the only candidate that can handily be derived from so-called renewable energy resources, and thus it can be expected to be used eventually as a fuel not only for aircraft but for other modes of transportation as well. However, we are unaware of any analysis that suggests LH$_2$ synthesis from these resources will be less costly or less energy intensive than obtaining hydrogen from coal gasification [12,15,16].

The last alternative selected for more detailed analysis was nuclear propulsion.

Refined Conceptual Designs

Refined conceptual design of airplanes using each of these fuels--JP, LCH$_4$, LH$_2$, and nuclear--were developed by the Air Force's Aeronautical Systems Division, which used its computer-aided design techniques. Each design was optimized to provide a minimum-gross-weight airplane meeting the previously presented design contraints. Additional constraints applied to the nuclear-powered airplane included takeoffs and landings using JP (i.e., with the reactor shut down), a reactor containment vessel designed to withstand a 350-fps impact, and an emergency cruise range, again using JP, of 1250 n mi. Safety motivates the former two constraints; recovery of the vehicle in the event of an emergency reactor shutdown, the latter. Fig. 1 shows general arrangements of the four designs. The fuel employed identifies each airplane: e.g., "VLA-NUC" designates the nuclear-fueled very large airplane (VLA).

The turbofan engines on the chemical-fuel airplanes incorporate modest advances in turbine-engine technology. The VLA-NUC employs dual-mode turbofan engines able to operate on either JP or an indirect-cycle,

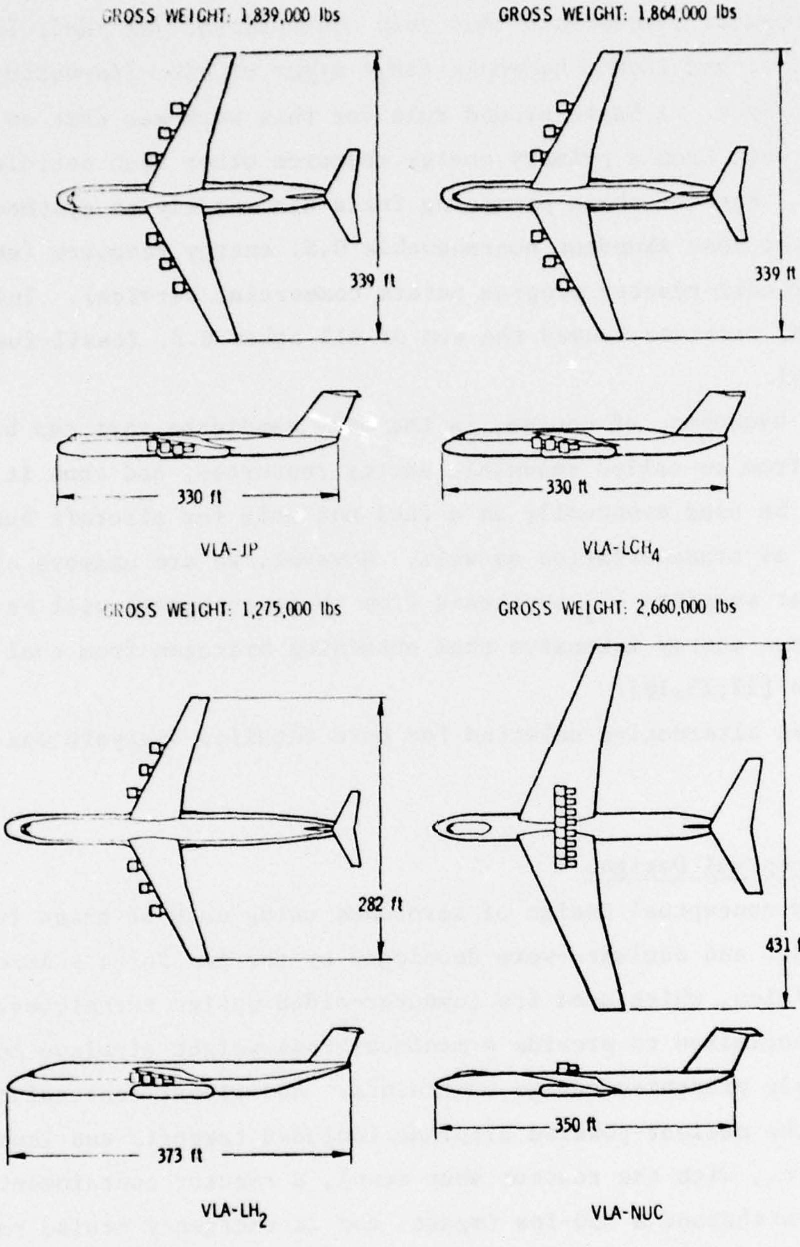

Fig. 1--General arrangements of the VLAs

liquid-metal-loop nuclear reactor system. All of the designs presuppose an all-aluminum structure.

Note the significantly larger fuselages of the airplanes utilizing cryogenic fuels. To illustrate this point, Fig. 2 shows the fuselage cross-section of each design.

Table 2 highlights some important weight and performance characteristics of the alternative airplanes. The C-5B has been included in the table as a benchmark to be representative of today's large airplanes. (The C-5B data reflect preliminary Lockheed estimates prepared in 1974 [10]. Of course, should the Air Force procure the C-5B, the design selected for production would almost certainly differ from the version used here as representative of a contemporary large airplane.)

Table 2

CHARACTERISTICS OF THE ALTERNATIVE AIRPLANES

Characteristic	C-5B	VLA-JP	VLA-LCH_4	VLA-LH_2	VLA-NUC
Weight, 10^3 lb					
Maximum gross takeoff	769	1839	1864	1275	2660
Operating empty	362	794	872	704	1907
Design payload	216	350	350	350	350
Performance[a] (nautical miles)					
Range	2730	6400	6500	6250	b
Radius	1560	3600	3600	3600	b
Radius-one outbound IFR	3110	5680	5570	6530	-
Radius-one outbound and one inbound IFR	4210	7450	7500	8750	-

[a]With design payload and assuming MIL-C-5011 A rules

[b]Essentially unlimited range and/or radius capability

Table 2 also compares performance with and without inflight refueling (IFR). We assume that each airplane is refueled by an airplane of the same type (i.e., the VLA-JP refueled by a tanker-configured VLA-JP).

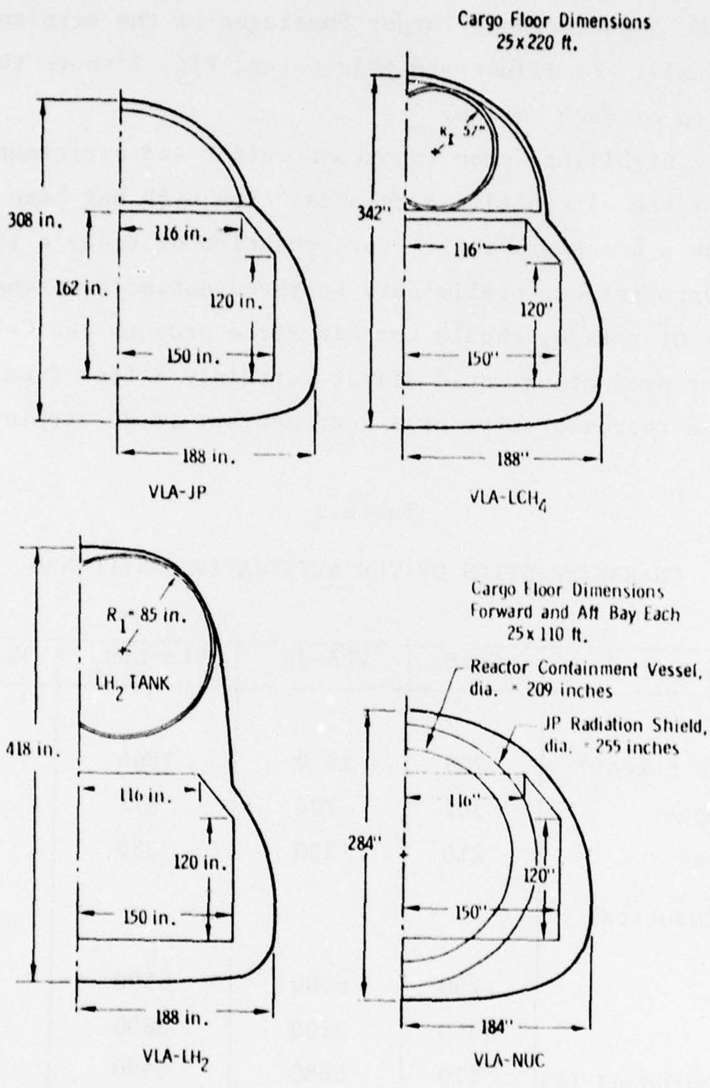

Fig. 2--VLA fuselage cross-section

Fig. 3 gives some insight into how the VLAs (in the cargo configuration) perform with other mission payloads. Even though the airplanes share a common payload-radius point (350,000 lb for a 3600 n mi radius mission), they exhibit grossly dissimilar payload-range characteristics. The nuclear airplane, an extreme of this point, has a payload capability independent of mission range.

Of particular interest, the VLA-LH_2 and the VLA-JP have comparable ranges at the design payload. For any other payload, however, the VLA-LH_2 has a markedly inferior range.

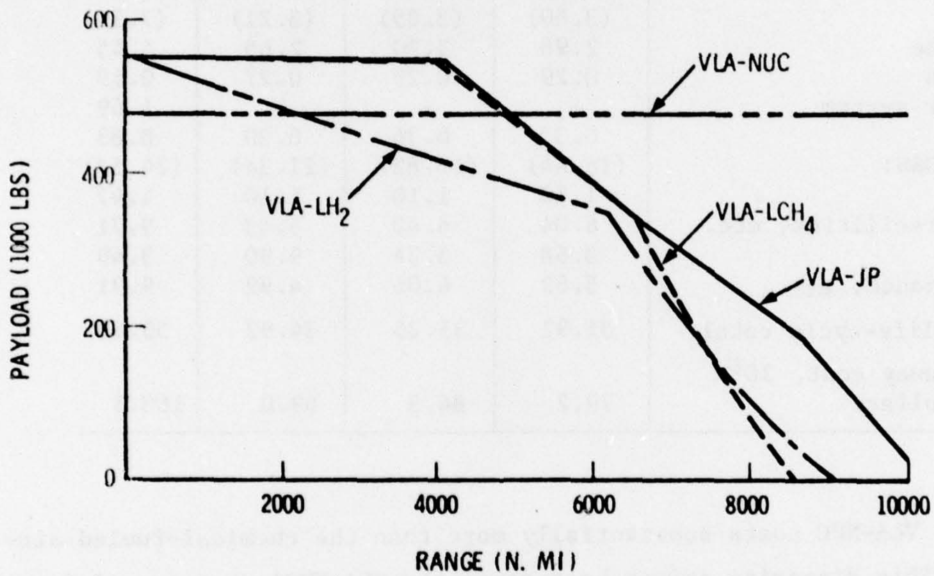

Fig. 3--Payload-range characteristics

Life-Cycle Costs

Table 3 presents estimates for the procurement, RDT&E (research, development, test, and evaluation), and O&S (operating and support) costs of the four VLAs. Except for fuel cost, the life-cycle estimates were developed using existing methodology [17].

Table 3

VLA LIFE-CYCLE COST ESTIMATES
OF 1975 DOLLARS UNLESS OTHERWISE STATED
(Assuming procurement of 129 aircraft
and 720 flying hours per year per UE)

Cost element	JP	LCH_4	LH_2	NUC
Procurement:	(11.88)	(12.67)	(10.35)	(24.89)
Airframe	8.19	8.86	7.24	12.62
Engines	1.86	1.88	1.50	1.36
Nuclear system	-	-	-	6.95
Other	1.83	1.93	1.60	3.96
RDT&E:	(3.60)	(3.85)	(3.21)	(7.16)
Airframe	2.98	3.20	2.65	4.45
Engines	0.29	0.29	0.27	0.19
Nuclear system	-	-	-	1.69
Other	0.33	0.36	0.30	0.83
20-Year O&S:	(16.44)	(18.83)	(21.34)	(24.58)
Crew	1.10	1.10	1.10	1.47
Fixed facilities, etc.	6.04	6.43	5.43	9.71
Fuel	3.68	5.24	9.90	3.49
Maintenance, etc.	5.62	6.06	4.92	9.91
20-Year life-cycle total	31.92	35.35	34.92	56.63
Unit flyaway cost, 10^6 1975 dollars	79.2	84.5	69.0	163.5

The VLA-NUC costs substantially more than the chemical-fueled aircraft. This disparity arises because of the VLA-NUC's heavier airframe and the expense of the nuclear system.

Variations in fuel costs account for much of the differences in total cost of the chemical-fuel airplanes. By identifying specific coal deposits and airbase supply points, we were able to include the associated fuel-distribution and -storage system in developing the following estimates for average delivered unit fuel cost [20]:

- $3.20/MMBtu (million Btu) for synthetic JP (i.e., about 39 cents a gallon).
- $4.30/MMBtu for LCH_4.
- $9.80/MMBtu for LH_2 (1975 dollars).

Fig. 4 gives a breakdown of the net costs of the synthetic fuels for two sets of financing assumptions. Note the large by-product credit for synthetic JP, due primarily to the substantial quantity of unleaded motor gasoline produced in the syncrude refining step. These estimates reflect actual costs of producing the synthetic fuel, including a 10-15-percent-discounted cash flow return on investment, but are not intended to reflect future fuel prices under actual market conditions.

In any case, our major concern is the relative cost, not the absolute cost, of producing the three fuels from the same resource, coal, and distributing them over the same supply network, in each case utilizing a similar, modestly advanced technology that would probably form the basis of any initial coal-based synthetic fuels industry in the U.S.

The average unit price of enriched uranium for the nuclear airplane was estimated as $0.65/MMBtu [10]. Despite this much lower unit energy cost, the twenty-year fuel cost shown in Table 3 for the VLA-NUC does not differ much from the VLA-JP's.

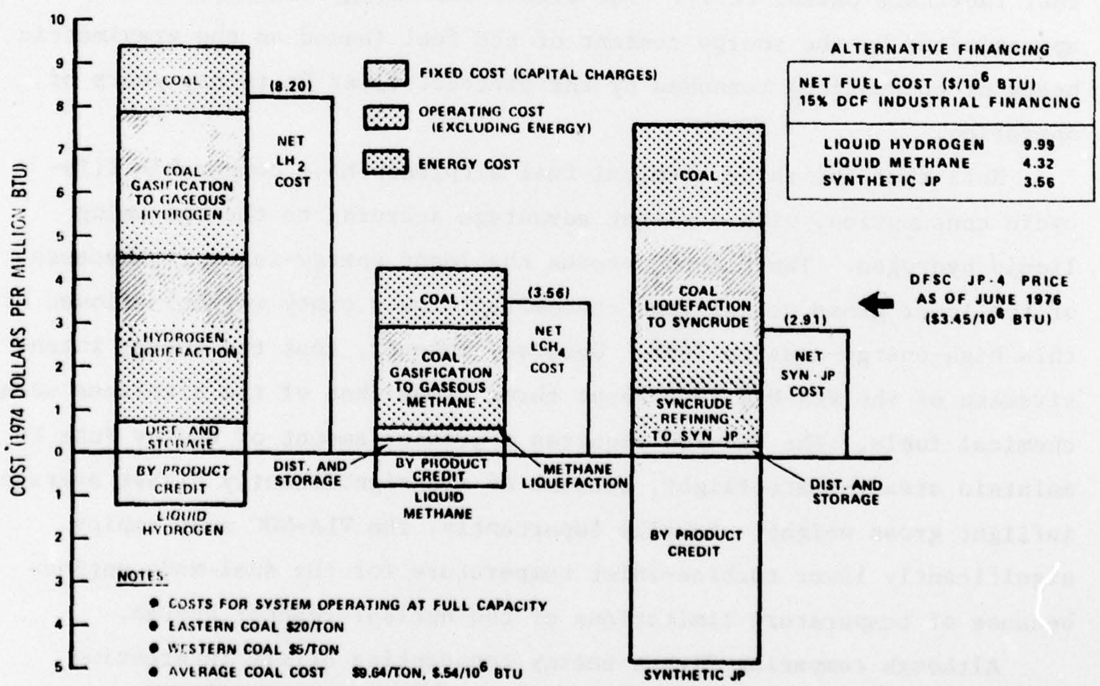

Fig. 4--Cost estimates for the synthetic chemical fuels

Life-Cycle Energy Consumption

Estimating life-cycle energy consumption proves less straightforward, inasmuch as little appropriate methodology has been developed for this purpose. We defined the life-cycle energy consumption of a fleet of aircraft as the energy expended in aircraft acquisition plus the energy embodied in the fuel consumed during twenty years of operation. The former directly depends on the quantity of aircraft procured; the latter also reflects the assumed utilization rate.

In what follows we discuss the four VLA options, using the same procurement/utilization assumptions as the previously described life-cycle costs, in terms of direct as well as total energy-consumption.

As the term implies, "direct energy consumption" means the energy directly consumed in building and flying the aircraft. Fig. 5 gives estimates of direct consumption for each of the VLAs. "Aircraft acquisition energy," for example, includes all of the energy consumed by the aircraft manufacturing facility (e.g., electricity for lighting, machines that fabricate parts, etc.). The direct O&S energy consumption is approximated by the energy content of the fuel (based on the gravimetric heats of combustion) consumed by the aircraft fleet in twenty years of operation.

Note that the three chemical-fuel airplanes have comparable life-cycle consumption, with a slight advantage accruing to the one using liquid hydrogen. The VLA-LH_2 proves the least energy-intensive because of the lower gross weight (and concomitant lower empty weight) allowed by this high-energy-density fuel. Observe, however, that the energy intensiveness of the VLA-NUC runs about three times that of the airplanes using chemical fuels. The VLA-NUC requires a greater amount of energy just to maintain steady-state flight, because of its significantly higher average inflight gross weight. Equally importantly, the VLA-NUC must employ significantly lower turbine-inlet temperature for the dual-mode engines because of temperature limitations of the nuclear-reactor system.

Although comparing direct energy consumption offers interesting insights, we believe that it does not give an appropriate measure of life-cycle energy. Rather, we believe the VLA options should be judged by their life-cycle *total* energy consumption.

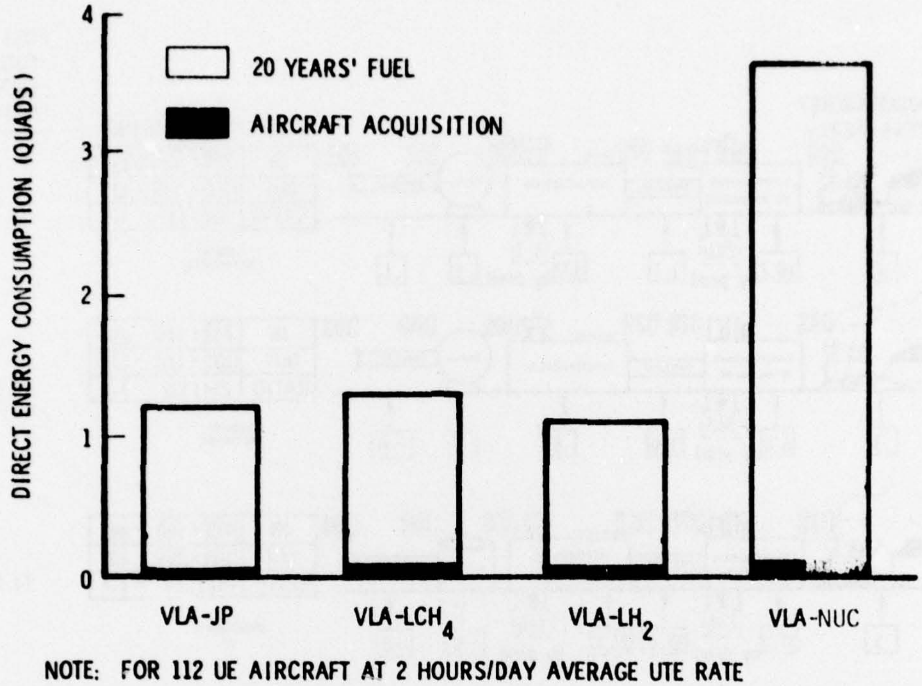

Fig. 5--Life-cycle direct energy consumption
NOTE: One quad is equal to 10^{15} Btu

Total energy can best be defined through the example of fuel energy. Direct energy consumption means the energy content of the fuel consumed on board the aircraft. Total energy consumption includes all of the energy expended in the fuel supply process as well.

Fig. 6 illustrates energy flows in the supply processes of the three synthetic chemical fuels as derived from coal [20]. Energy expended beyond the useful output (i.e., energy lost) includes

- o Thermodynamic losses in the various conversion steps (e.g., coal gasification or liquefaction).
- o Process energy requirements (e.g., electricity required to liquefy gaseous hydrogen.)
- o Distribution and storage losses.
- o Energy expended in building the required facilities [21].

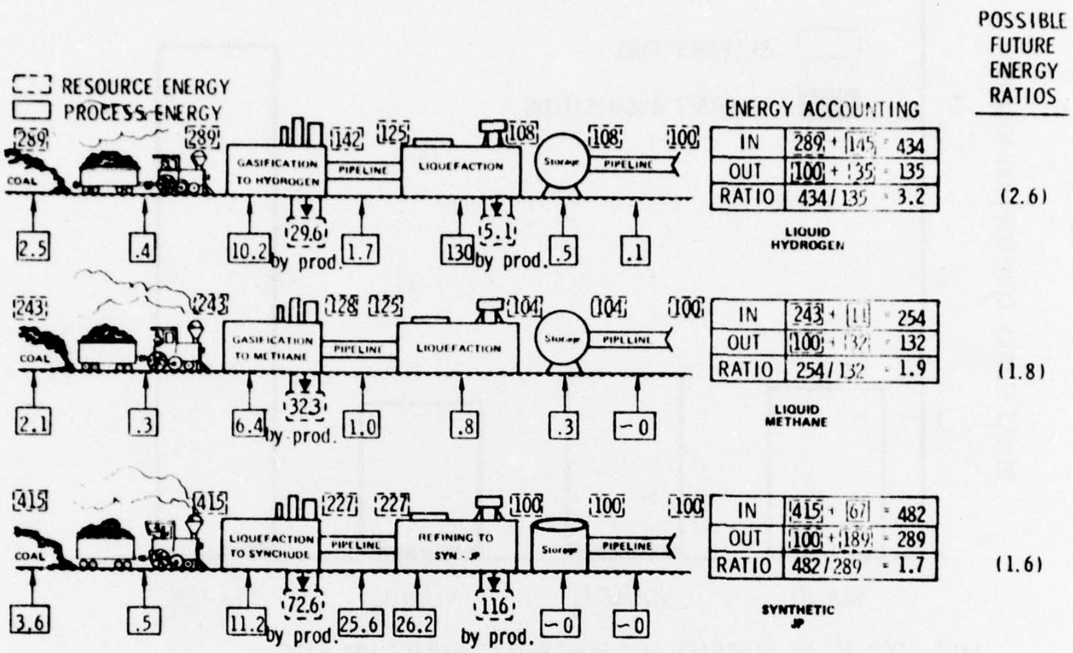

Fig. 6--Energy flows in the synthetic fuel supply processes

Energy intensiveness can be then measured in terms of the energy ratio defined as the ratio of total energy input to useful energy output. By way of comparison, today's crude oil supply system is characterized by an energy ratio of approximately 1.2. These energy flows show the liquid-hydrogen process to be significantly more energy intensive than the other fuels; LH_2 would accordingly profit the most from advances in technology, particularly from efficiency improvements in electric power generation, since large amounts of electricity are required for hydrogen liquefaction. As a consequence, to give the more exotic cryogenic fuels some benefit of the doubt over the more conventional, synthetic-JP alternative, we use the more optimistic energy ratios.

Thus, total fuel-energy consumption can be obtained by multiplying direct consumption by the appropriate energy ratio.

An analogous energy ratio for the fuel cycle of the nuclear airplane was also developed with resource energy flows based on the energy content of the fissionable uranium isotope U^{235}. We assume recovery of most of the unused energy embodied in the reactor core at the end of 10,000 reactor-hours. This rather conservative view (in the sense that other plausible

assumptions would yield substantially higher energy ratios) of the energy flows in the nuclear fuel cycle yields an energy ratio of approximately 1.5.

Fig. 7 summarizes life-cycle total energy consumption for each of the very large airplanes. Because of the energy intensiveness of the liquid-hydrogen supply process, the VLA-LH_2 is the largest consumer of energy among the chemical-fuel options. The VLA-NUC remains the most energy-intensive. However, comparing the VLA-NUC with the chemical-fuel airplanes is difficult because of the different resource bases being exploited. For example, if nuclear energy were far more abundant than coal, then the greater energy-intensiveness of the nuclear airplane might be of little significance. In fact, without the breeder reactor, U.S. coal reserves exceed uranium reserves (in terms of energy content) by almost an order of magnitude. The breeder reactor would reverse this situation [6].

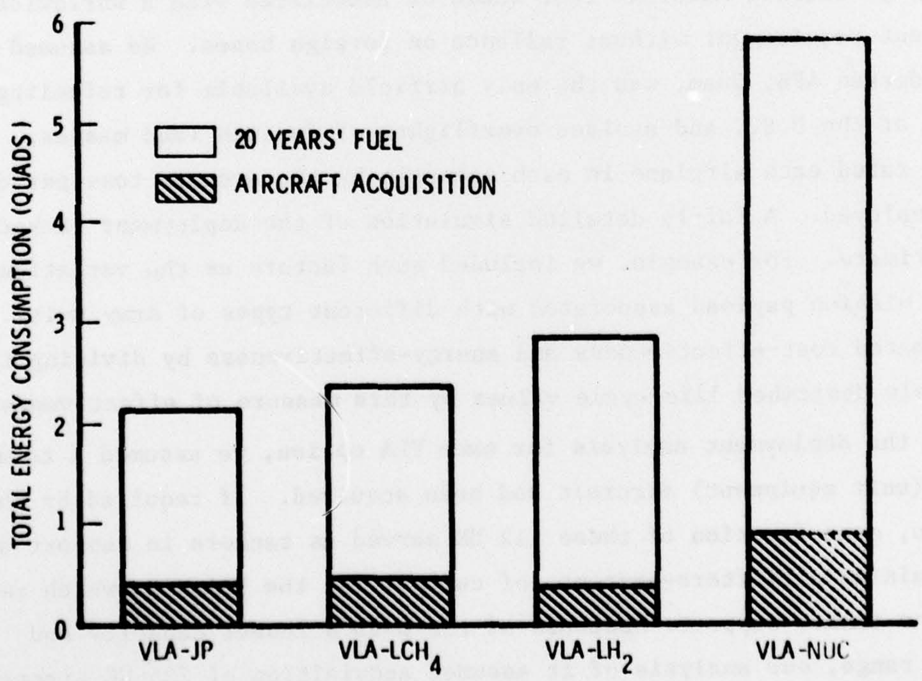

Fig. 7--Life-cycle total energy consumption

MISSION ANALYSIS

To investigate the cost- and energy-effectiveness of the four airplanes, we analyzed them in the context of the potential missions described earlier. A detailed analysis of the strategic airlift mission provides insights into the utility of VLAs as airlifters and tankers. The remaining missions, which we term "station keeping," have been investigated generically.

Strategic Airlift Missions

Given the importance of strategic airlift in providing mobility to general-purpose forces [2], our analysis of the very large airplanes used a detailed simulation of the deployment of Army combat and support units to various parts of the world. For each deployment destination considered, we examined both range and radius missions. The latter assumed that fuel for the return flight of the airlifter was either unavailable (or at a premium) at the destination. The scenarios were intended to reflect the spectrum of airlift missions that would be associated with a worldwide deployment requirement without reliance on foreign bases. We assumed that Andersen AFB, Guam, was the only airfield available for refueling outside of the U.S., and avoided overflights of foreign land masses.

We rated each airplane in each scenario by the average tons per day being deployed. A fairly detailed simulation of the deployment backed each estimate. For example, we included such factors as the variation in average mission payload associated with different types of Army units. We estimated cost-effectiveness and energy-effectiveness by dividing the previously described life-cycle values by this measure of effectiveness.

In the deployment analysis for each VLA option, we assumed a total of 112 UE (unit equipment) aircraft had been acquired. If required by the scenario, some fraction of these 112 UE served as tankers in support of the remaining airlifters--except, of course, for the VLA-NUC, which requires no tanker support. Because of the C-5B's lesser capacity and shorter range, our analysis of it assumed acquisition of 225 UE aircraft.

Table 4 summarizes relative cost-effectiveness and energy-effectiveness of the VLA options and the C-5B for each of six strategic-airlift scenarios investigated. For simplicity, we have normalized these results

to the cost-effectiveness and energy-effectiveness of the C-5B when flying the NATO-range mission. *Under these circumstances*, the smallest relative cost or relative energy in Table 4 for each scenario indicate the most attractive choices.

Table 4

RELATIVE COST-EFFECTIVENESS AND ENERGY-EFFECTIVENESS FOR STRATEGIC AIRLIFT MISSIONS

Airlift Mission	C-5B	VLA-JP	VLA-LCH$_4$	VLA-LH$_2$	VLA-NUC
Relative cost					
NATO range	1.00	1.06	1.24	1.28	1.63
NATO radius	1.23	1.01	1.12	1.14	1.46
Middle East range	1.84	1.65	1.86	1.88	2.57
Middle East radius	18.52	2.67	2.38	2.32	2.32
Far East range	1.84	1.95	2.25	2.23	3.09
Far East radius	1.53	1.34	1.56	1.86	2.75
Relative energy					
NATO range	1.00	0.73	0.90	1.08	1.74
NATO radius	1.23	0.70	0.82	0.97	1.56
Middle East range	1.84	1.13	1.36	1.59	2.74
Middle East radius	18.52	1.83	1.74	1.96	2.47
Far East range	1.84	1.33	1.64	1.88	3.30
Far East radius	1.53	0.92	1.14	1.56	2.93

Most attractive   Intermediate   Least attractive

In the NATO-range mission, none of the VLAs is more cost-effective than the C-5B; but in terms of energy the C-5B appears considerably less attractive.

For the NATO-radius mission, on the other hand, the three chemical-fueled VLAs show less relative cost than the C-5B.

It is interesting to note that the mission profiles flown on the NATO-range mission correspond approximately to the C-5B's design point, whereas the VLAs' design point corresponds essentially to the profiles for the NATO-radius mission. Thus, the remaining missions provide insights to the off-design performance of all the aircraft.

Table 4 has two purposes: first, to show how the relative cost and relative energy of the VLAs and C-5B change for six different mission scenarios and, second, to aid in selecting the most attractive airplane from an overall viewpoint. To help in this selection, Table 4 shows for each mission scenario the relative ranking--most attractive, intermediate, or least attractive--of each airplane, based on relative cost and relative energy. For example, for the NATO-range mission, the C-5B and the VLA-JP are clearly the most cost-effective, the VLA-NUC the least cost-effective, and the airplanes using cryogenic fuels of intermediate cost-effectiveness. Of course, the relative importance of each scenario should be carefully weighed, since some missions are clearly more significant than others.

Overall, it would appear that the VLA-JP proves the most attractive of the options. However, careful consideration shows that if you discount the Middle East-radius mission the VLA-JP does not overwhelmingly dominate the C-5B--at least, in terms of cost-effectiveness. None of the other options reasonably challenges the superiority of the VLA-JP.

Station-Keeping Missions

We have classified the missile launcher, tactical battle platform, maritime air-cruiser, and C^3 platform as station-keeping applications. That is, the required flight profile in each of these missions can be characterized by the distance from the base to the station-keeping point (station radius) and the station-keeping duration (time-on-station).

Fig. 8 indicates some of the rationale for adapting this approach, which associates some station-keeping missions with appropriate station radii. Note that none of the missions requires a station radius greater than about 7000 n mi. Some missions (e.g., ASW) require long station-keeping; others, such as the tactical battle platform, suggest a much shorter time on station, particularly under wartime conditions, when munitions and other supplies are being rapidly expended.

An analysis similar to that of the strategic airlift mission was performed by considering both short (12-hr) and extended (324-hr) times on station for each of the station radii highlighted in Fig. 8. Life-cycle-cost and energy-consumption calculations were predicated on a second aircraft buy of as many UE as acquired for the strategic airlift mission, as discussed above. That is, additional aircraft were procured

on the assumption that the first buy would be for airlifters/tankers; consequently, no R&D costs are associated with the station-keepers. The maximum payload tonnage that could be maintained on-station continuously was selected as the effectiveness measure.

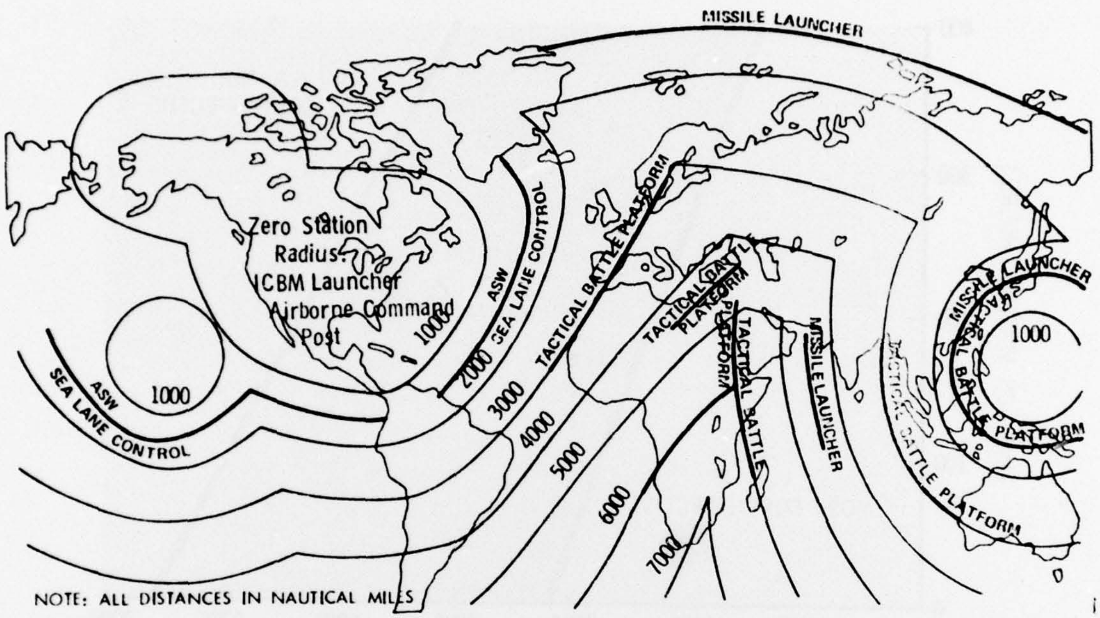

Fig. 8--Potential station-keeping missions matched with approximate contours of equal distance from airbases in the United States and Guam

Comparison of cost-effectiveness and energy-effectiveness showed the VLA-JP to be the most attractive plane for the smaller station radii. The VLA-NUC was the most attractive for the larger radii. Compared with these two, the other options displayed significantly inferior characteristics.

Fig. 9 underscores the relative cost-effectiveness of the VLA-JP and VLA-NUC. (In terms of energy-effectiveness, the VLA-NUC proves superior only at the very largest station radii.) Within the "region of uncertainty," either plane can be described as "most cost-effective"--depending on one's perspective (e.g., whether or not costs are discounted to reflect a time preference for expenditures) or the operational concept employed. The VLA-NUC begins to dominate the VLA-JP at station radii greater than 4000 n mi.

Interestingly, Fig. 8 suggests that the most prominent large-radius mission would be the tactical battle platform. As noted, time on station may be limited for such missions. As shown in Fig. 9, that limitation would not favor the nuclear-powered airplane.

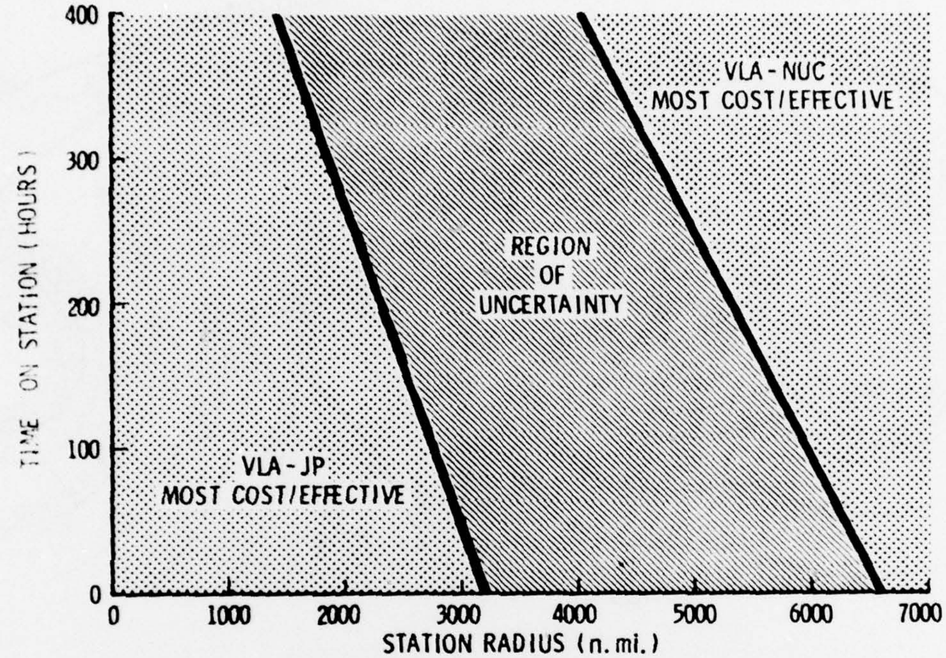

Fig. 9--Comparison of the VLA-JP and VLA-NUC in the station-keeping role

<u>CONCLUSIONS AND OBSERVATIONS</u>

The major conclusions of this analysis, as well as some observations regarding the effects of uncertainty on our results may be summarized as follows:

Regarding the most attractive fuel alternative:

o Overall, a conventional hydrocarbon jet fuel (derived from either petroleum, oil shale, or coal) remains the most attractive fuel for military aircraft. Although based on an analysis of very large airplanes (VLAs), this conclusion should apply to all classes of military airplanes except hypersonic vehicles.

- o Liquid methane and liquid hydrogen offer little potential as military aircraft fuels, at least until readily extractable U.S. petroleum, oil shale, and coal resources approach exhaustion.
- o Nuclear propulsion for aircraft is attractive only for station-keeping missions requiring large station radii (greater than about 4000 n mi).

Regarding the potential of advanced-technology large airplanes:

- o Very large airplanes may not be substantially more cost-effective than today's airplanes for some strategic-airlift missions.
- o If the capability to airlift U.S. forces worldwide without reliance on overseas bases is perceived as a requirement, VLAs become very attractive--particularly if refueling at the destination cannot be guaranteed.
- o For station-keeping applications, VLAs prove clearly superior to today's equipment.

Note, however, that we have not concluded that the design constraints imposed on VLAs define the most desirable characteristics for the next generation of large airplane. Rather, we simply point out that an advanced-technology airplane with significantly greater capability than any existing equipment is an attractive option.

Many factors enter into any broad-brush systems analysis, and each factor has some uncertainty associated with it. One such factor concerns the implications of advanced aircraft technology. The VLA conceptual designs used in this article incorporate little advanced technology. If they did, it is reasonable to expect that their superiority relative to today's airplanes would be even greater. Furthermore, advanced technology would benefit the VLA-JP more than the other VLA options, since any technical advance, in simplest terms, merely reduces the energy requirements of the aircraft. The resulting reduction in aircraft gross weight is most pronounced for the VLA-JP because JP has the highest weight per unit energy of all the chemical fuels. Because reactor system weight is not a strong function of design power level, the nuclear airplane is also at a disadvantage in this regard [10].

In addition, throughout our analysis many uncertainties have been resolved, by intent, in favor of options other than the VLA-JP. That the VLA-JP still evolved as the most cost-effective and energy-effective option defines, in our view, a powerful result (i.e., a classical *a fortiori* analysis).

In brief, conventional jet fuel (JP)--made from coal, oil shale, or crude oil--appears to be the most attractive aviation fuel for future Air Force use. This conclusion should be valid for all airplanes entering the inventory before the year 2000. Furthermore, a JP-fueled airplane with a maximum gross weight exceeding a million pounds should be more cost-effective and energy-effective in a wide variety of missions than any of today's airplanes.

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